Imaging sensor technology for intelligent vehicle active safety and driver assistant systems

Bakhtiar B. Litkouhi*

Perception & Vehicle Control Systems
Electrical & Controls Integration Lab
GM Global R&D
Warren, MI 48909-9055
E-mail: bakhtiar.litkouhi@gm.com
*Corresponding author

Yuri Owechko, Vikas Kukshya and Rajesh Rajavel

HRL Laboratories LLC,
3011 Malibu Canyon Rd.,
Malibu, CA 90265, USA
E-mail: yowechko@hrl.com
E-mail: vkukshya@hrl.com
E-mail: RDRajavel@hrl.com

Abstract: Vehicular Active Safety and Driver Assistant Systems (ASDASs) rely heavily on sensors for achieving their goal of protecting the driver and passengers from potentially dangerous situations. The list of such sensors includes imaging sensors operating in different wavelength bands of the visible (i.e., video cameras) and IR spectrum, as well as ranging sensors such as ultrasonic, radar and lidar. The non-imaging ranging sensors are useful for applications that do not require object recognition/classification or scene understanding, but they generally have poor angular resolution and do not provide much information on the spatial characteristics of objects, making object recognition or classification and lane following difficult or impossible using such sensors alone. On the other hand, inexpensive vision sensors can capture the scene image in high spatial resolution and a wide field of view, which makes them ideal for object recognition and lane following under most conditions. The objective of this 'Over the Horizon' (OTH) sensor technology overview is to explore emerging imaging sensor technologies that can lead to significant capability improvement as well as cost reduction for future automotive driver assistance and active safety systems. The technologies covered include visible, IR and hyperspectral imaging systems. We also discuss 3D imaging systems. We provide a summary description of different sensors/systems, system architecture and implementation, as well as cost/performance tradeoffs, technology gaps, deployment scenarios and technology trends in the near-, mid- and long-term.

Keywords: intelligent vehicles; active safety; driver assistant; imaging sensors; active sensors; automotive applications.

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Biographical notes: Bakhtiar B. Litkouhi joined GM in 1985. Since 2004, he has been the Manager of the Perception and Vehicle Control Systems Group. From August 2006 to March 2007, he was also the Acting Director of the Electrical and Controls Integration Lab at GMR&D. He is a Board Member of ITS-MI and the University of Waterloo WatCAR Program. In addition to his current responsibilities, he is the Program Manager for the GM-Carnegie Mellon University Autonomous Driving Collaborative Research Lab. Prior to joining GM, he was an Assistant Professor at Oakland University, Rochester, Michigan. He holds a BSc in Mechanical Engineering, MSc in Applied Mathematics and PhD in Systems Science, specialising in Controls. He has served as the program manager for several large scale projects in intelligent vehicle systems, advanced chassis control, human machine interface, systems engineering and control integration, where he has made numerous contributions through publications and presentations. He owns numerous patents and record of inventions in different areas of his activities.

Yuri Owechko is a Principal Research Scientist in the Information and Systems Sciences Laboratory of HRL Laboratories, LLC. He received his BS in applied physics from Caltech in 1978 and his PhD in materials science from the University of Southern California in 1983, where he conducted research on spatial light modulators for optical processing systems. Since joining HRL, he has conducted research in optical signal processing systems, as well as in algorithm development for video and LIDAR-based object recognition, machine learning, resource allocation, evolutionary optimisation methods, time-frequency and wavelet transforms, smart antenna signal processing and compressive sensing in projects for GM, Boeing and DARPA, including DARPA's URGENT and KECoM programmes. He has a total of 76 technical publications, 46 issued patents and 18 patents pending.

Vikas Kukshya (IEEE S'99 – M'01 – SM'06) received the B.E. degree in Electronics and Communications Engineering from Gujarat University, India in 1997. He graduated at the top of his class and was awarded three gold medals by the University for Academic Excellence. He graduated Summa Cum Laude with an M.S.E.E. degree from Virginia Polytechnic Institute and State University in 2001. At Virginia Tech, he worked with Prof. Theodore S. Rappaport at Mobile and Portable Radio Research Group specialising in wideband propagation measurements and channel modeling. Since 2001, he has been with HRL Laboratories LLC, Malibu, CA, where he has performed research on such diverse topics as wideband millimeter-wave and free-space photonics communication systems, inter- and intra-vehicular wireless communications and networking, software-defined-radios, and advanced analog- and digital-signal-processing for real-time hyperspectral target detection, real-time radar based tracking, compressive sensing, blind-source-signal-separation, and blind knowledge-enabled beamforming. He has authored over 15 conference or journal papers, and holds 2 U.S. patents.

Rajesh Rajavel is the Manager of the Detector Materials Technologies Department at HRL Laboratories, where he is involved in the development of III-V and II-VI based IR detectors, including III-V Sb-based FPAs, InGaAs-based APDs and HgCdTe-based IR detectors. He serves as the Program Manager for the MDA/FastFPA and DARPA/PT-SQUAD programmes devoted to the development of III-V IR FPAs. Prior to his present position, from 2000 to 2006, he was involved in device design, epitaxial growth, characterisation and processing of high-speed InAs and InP-transistors and InGaAs-based photonic devices at HRL. From 1991 to 2000, he worked on HgCdTe-MBE technology for producing high performance dual-band infrared detectors and improving yield and performance of IR detectors. He received his PhD from the Georgia Institute of Technology in 1991. He has co-authored two book chapters, over 75 technical papers and has thirteen issued patents.

1 Introduction

In 2009, a total of 33,808 people died in motor vehicle traffic crashes, a 9.7% decline from the 37,423 deaths reported in 2008 and the lowest number of deaths since 1950 (which had 33,186) [http://techdailydose.nationaljournal.com/2011/01/test.php]. Passenger car occupant fatalities have declined for the seventh consecutive year and are at their lowest level since the National Highway Transportation Safety Administration (NHTSA) began collecting fatality crash data in 1975 [DOT HS 811 172, 2008]. These encouraging statistics have arisen partially as a result of the emphasis laid by the US Department of Transportation (DOT) and the automotive industry on vehicle safety improvements through the development of new vehicle safety systems that generate timely information and warning to reduce driver error and vehicle crashes.

Robust Active Safety and Driver Assistant Systems (ASDASs) need sensor systems that provide a seamless sensing field surrounding a vehicle to detect road hazards or targets of importance to the task of driving and to potentially warn the driver and assist in avoiding/mitigating crashes.

Existing ASDAS sensors for the most part operate as an individual sensor with a designated function, such as object detection, ranging or imaging for collision avoidance, road hazard and emergency detection. The list of such sensors includes imaging sensors operating in different wavelength bands of visible (i.e., video cameras), IR spectrum and hyperspectral imagers, as well as ranging sensors such as radar and lidar. These discrete sensors at times exhibit performance limits that reduce the robustness of safety systems under certain operating conditions and constrain their effectiveness under various environments and vehicle operation conditions. The performance shortfalls of discrete sensors can be improved with new technology or by fusing data from multiple sensors to produce a more comprehensive vehicle situation assessment. As the performance and the economics of various sensor technologies improve over time, various sensor suites with data fusion capability matched to appropriate ASDAS application needs are most likely to be adopted into future ASDASs. With the cost consideration always being a priority in the implementation of such systems, many vehicle safety system engineers have assumed that new sensor technologies will not only enhance the capability but also reduce the cost of ASDAS in future vehicles.

The objective of this 'Over The Horizon' (OTH) sensor technology overview is to explore emerging sensor technologies that can lead to significant capability improvement as well as cost reduction for future automotive ASDASs. We have identified several OTH sensor technologies, either in development or yet to emerge, that promise improved sensor performance for ASDAS applications over what is possible today. Candidate sensor technologies examined in this paper focus on imaging sensors, including vision sensors in visible, near-, mid- and far IR bands; 3D imagers; and hyperspectral imagers.

2 Sensor technologies for active safety and driver assistant systems

Proximity sensors (including capacitance and acoustic sensors), radar ranging sensors and vision sensors (including 2D and 3D imaging sensors), are the three relatively low-cost sensor technologies that have been developed for vehicle ASDAS applications. In many ways, these sensing technologies are complementary. Proximity sensors detect the presence of object(s) in close range at very low cost. Radar ranging sensors provide accurate distance and Doppler measurements for multiple objects under almost all environmental conditions. Such cost-effective ranging sensors are useful for applications that do not require object recognition or scene understanding (such as adaptive cruise control or collision warning, although false alarms may occur from overhead bridges and other structures), but they generally have poor angular resolution and do not provide much information on the spatial characteristics of objects, making object recognition or classification and lane following difficult or impossible using such sensors alone.

A fourth category of sensor, mechanical laser scanning systems (LIDAR), has been used successfully in various autonomous vehicle demonstrations such as the DARPA Grand Challenge (2005–2006) and Urban Challenge (2007). Though these systems provide accurate 3D information over a wide range of conditions, the high cost, size and questionable durability of such systems make them less attractive for consumer automotive applications.

While sensitive to some environmental conditions such as rain or fog (as are humans), vision sensors capture the scene image in high spatial resolution and a wide field of view at a low cost, which makes them ideal for object recognition and lane following under most conditions. In addition, 2D vision sensors, being passive in nature, do not raise concerns regarding acceptable levels of output power. A vision sensor with robust computer vision and image processing algorithms can extract salient scene information for vehicle ASDAS applications. Future ASDAS applications, such as pre-crash sensing, adaptation for collision avoidance or mitigation, pedestrian detection, etc., will perform best with a multi-sensor system and dynamic data fusion algorithms to understand the scene surrounding the vehicle.

In this overview, we focus on the current status and future trends in vision sensors for ASDAS. In the following sections, we will discuss technical characteristics of vision sensors that utilise visible, IR and hyperspectral wavelengths. In addition, we discuss emerging OTH technologies that promise new and enhanced capabilities for these sensors.

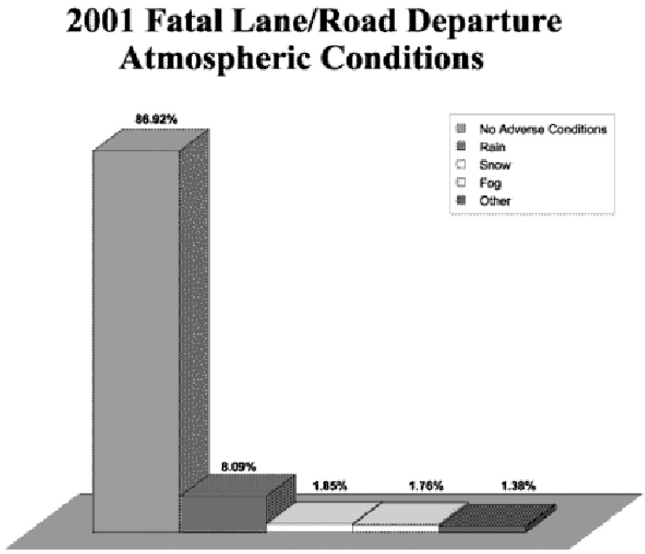
2.1 2D and 3D vision sensors

In this section, we discuss visible and near IR (<1 μm wavelength) vision sensors (or imagers) based on silicon technology that include silicon-based Charge Coupled device (CCD) vision sensors and CMOS (complementary metal-oxide-semiconductor) vision sensors (CVSs). We also discuss smart vision sensors with processing elements integrated in every pixel, 3D scene sensing imagers that utilise time-of-flight measurements to reconstruct a 3D scene and computer vision algorithms for their potential impacts on ASDAS sensor design in automotive applications. We will review the current and projected capabilities of CMOS silicon vision sensors in terms of resolution, dynamic range and integrated image processing functionality. Already, techniques have been demonstrated for creating silicon-based image mosaics with very high resolution and a wide field of view in real-time using multiple cameras, 3D scene reconstruction from multiple views, super-resolution and active vision systems that mimic the tracking behaviour of biological vision systems. We will also examine the design flexibility and cost effectiveness of CMOS silicon vision sensors for ASDAS applications.

2.1.1 Functionality

Low–cost, compact silicon-based vision sensors operating in visible and near IR (wavelength < 1 μm) with adequate dynamic range and response time can capture scene images with sufficient spatial resolution for automotive applications. Since vision is the main sensing modality used by human drivers, visual images must contain sufficient information for virtually all ASDAS applications. Since most fatalities and accidents occur under 'normal' driving conditions with good visibility (see Fig. 1), the degradation of vision sensor information under adverse environmental conditions may not be a major barrier to the deployment and implementation of vision-based driver assistant systems. The main challenge for silicon-based vision sensors in meeting automotive ASDAS requirements is the dynamic range of the sensor, defined as the ratio of full-scale incident flux from a bright object to the noise equivalent flux of the sensor from a dim object. Both intra-scene and inter-scene wide dynamic ranges are important, since the vision sensor must handle a large range of lighting conditions from night time to daytime and also scenes where objects in both dark shadow and bright sunlight must be seen in the

Figure 1 NHTSA statistics for dependence of 2001 fatal lane/road departure fatality rates on atmospheric conditions (US Department of Transportation (DOT), 2009). 0.87% of fatalities occurred under non-adverse conditions



same image. An intra-scene dynamic range of 110–120 dB is desirable to prevent image bloom-out. Such a vision sensor integrated with computer vision algorithms can extract pertinent scene information under most day and night weather conditions. The implementation of vision algorithms requires high performance solid state imaging processors with high computational throughput. The speed, detection and false alarm rates of current vision systems can also be improved by a hybrid system design where a vision subsystem is cued by a ranging sensor such as radar, LIDAR, or the 3D imaging CMOS sensors, discussed below.

2.1.2 Vision sensor types

2.1.2.1 CCD and CVS

The two main silicon-based vision sensor technologies for visible and near-IR wavelengths are CCD and CMOS vision sensors (CVSs). Bell Labs demonstrated the first CCD vision sensor in 1970 and CCDs remained the dominant solid-state imaging technology until the mid-1990s. In the forty years since their invention, CCD vision sensors have achieved a high level of performance with their high sensitivity and uniformly low noise pixels, high dynamic range, small pixel size, low complexity and large array size (Tipnis et al., 1999). CCD technology is now relatively mature, but it remains relatively non-optimal and inflexible in terms of meeting the performance and cost needs of commercial markets such as digital cameras and automotive ASDASs. CCD fabrication processes are not compatible with conventional CMOS processing and do not allow easy integration of on-chip ancillary circuits such as analogue-to-digital converters and signal processors. As a result, CCD vision sensors require multiple IC chips which increase power consumption, package size and product cost. The architecture and processing requirements of CCDs also prevent the integration of circuitry at each sensing element or pixel (active pixels). Active pixels are especially useful for extending the dynamic range without reducing readout rates, increasing pixel size, or cooling. In addition, the charge-transfer nature of CCDs prevents 'area of interest' readout: the entire image must be read out even if processing is to be done on only a sub-region of the image, which reduces system efficiency and speed.

CVS has an advantage over CCD from the standpoint of its sensor dynamic range, mainly as a result of its architecture flexibility that allows in-pixel signal processing for dynamic range enhancement (Carlson, 2002). CCD imagers achieve high dynamic range by keeping the noise level of pixel readout to a low level using high quality silicon processing, cooled operation and slow readout, which increases cost and reduces frame rates. Uncooled consumer-grade and high-end CCD imagers achieve dynamic ranges of about 66 dB and 78 dB, respectively. In contrast, a conventional consumer-grade CVS without on-chip processing has a dynamic range of only about 54 dB. However, the architecture flexibility of CVS allows high dynamic ranges of up to 154 dB to be achieved using various active-pixel circuitries and operating modes without sacrificing frame rates or increasing cost, although SNR can be reduced (see Section 2.1.4).

2.1.2.2 Smart CVS

'Smart' vision sensors[1] incorporate circuitry in each individual smart pixel to perform various image processing functions by communicating with other pixels in the local neighbourhood.

Many of the smart vision sensors implemented thus far were inspired by biological early vision systems. They perform relatively low level operations such as extracting edges, motion detection, orientation detection, time-to-crash determination, foveation (non-uniform image resolution), etc., using local neighbourhood communication between pixels. Higher level functions such as object recognition typically require global gathering and communication of information and cannot be easily implemented using locally interconnected smart pixel arrays alone. By locating the sensing and processing elements in close proximity directly on the imaging chip, image processing operations can be performed with a very high degree of parallelism, small packaging and low power consumption.

A disadvantage of smart vision sensors is that the addition of processing circuitry increases the size of individual pixels, which reduces the image resolution for a given chip size and it also reduces the fractional photosensitive area, which in turn reduces sensitivity and dynamic range for a given pixel size. Another disadvantage is the limited programmability of these special-purpose sensors, since the functions are hardwired. In general, it is difficult to design a smart vision sensor that incorporates both high quality imaging characteristics (high dynamic range, high spatial resolution/pixel count, high sensitivity) and pixel-parallel image processing functions.

2.1.2.3 3D CVS

Over the past few years, visual sensing technologists have successfully demonstrated high rate recording of perfectly registered 2D reflectivity and 3D range images using low cost CMOS imaging chips. The ability to image 3D scenes allows robust detection, recognition, tracking and measurement of objects both outside and inside the car for collision avoidance, safety, security and convenience applications. The perfect registration of conventional intensity and range images is very useful for vision applications, since foreground objects can be easily segmented from background ones and object texture mapping is automatically maintained. Both shape and texture features can be easily fused and used for recognition and tracking.

Unlike stereo vision approaches for 3D imaging, a 3D CVS imager uses a single sensor with active pulsed or modulated illumination. By measuring the time of flight between emission of the pulse and detection of the reflected light for each pixel in an imaging array, the range can be measured with resolution independent of object range. Pulsed illumination is advantageous for outdoor long range applications because of the higher peak power that can be achieved. It is also possible to 'see through' foliage or other porous objects by exploiting small gaps and using time-gating to filter out reflections from the foliage. The use of a single sensor also increases mounting flexibility and eliminates calibration issues that must be considered when using stereo vision for range measurement, since stereo baseline considerations are eliminated. Another advantage over stereo vision is the ability to determine the range of objects with uniform or featureless surfaces. Stereo vision uses the disparity or difference in position of a feature seen in both cameras to determine the range to the feature; thus, a critical part of stereo vision is finding corresponding feature points, which is difficult to do for uniform surfaces.

The illumination for 3D CVS is modulated light from either an array of near-IR LEDs or a semiconductor laser that illuminates the entire scene. The modulation can be continuous or pulsed. The reflected light is then imaged and analysed for range information at each pixel. Since the illumination is not scanned, no mechanical movement is utilised and the entire sensor can be integrated in CMOS, which makes the system much more compact, less expensive, simpler, more power efficient and more robust than LIDAR approaches, which utilise a laser beam that is mechanically scanned using rotating mirrors. The need for a small focused spot also requires relatively large optics for scanning LIDAR systems. By illuminating the entire scene, the 3D CVS illumination optics can be made very compact. Using LEDs instead of a focused laser also reduces perceived eye safety concerns by using a non-coherent beam as well as by lowering the sensor cost. 3D CVS takes advantage of recent progress in CMOS vision sensors and LED lighting products. Since near-IR LEDs are already being considered for headlight augmentation for night vision systems, they could also be used for 3D CVS. A 3D CVS imager can be used for multiple functions: collision avoidance, smart cruise control (potentially replacing radar/lidar), parking assistant, backup warning, pedestrian and vehicle detection, pre-crash sensing, sign detection, navigation aids, occupant sensing for smart airbags and vehicle security.

Since a 3D CVS utilises a single imaging sensor, absolute range must be measured using the time-of-flight principle (as opposed to the disparity or triangulation principle behind stereo vision, which requires a nonzero baseline separation between cameras). Three basic technologies have been developed for measuring range with an imaging sensor array: digital time counters, range-gated imagers and RF-modulated light sources with phase detection.

In the digital time counter approach, a fast digital counter circuit is integrated into each pixel. The counting starts when a light pulse is emitted and stops when the return light is detected, thereby measuring the delay and hence, the range for that pixel. One advantage of the digital counter approach is that digital gating can be set to reduce scattered light and record signals from a given range window, thereby improving visibility in rain, snow, fog and smoke. It can also be used to see through foliage and other porous objects as described previously. By using a powerful laser diode, a narrow field of view and large aperture collection optics, ranges of greater than several kilometres with an imaging resolution of 128×128 and 30 Hz frame rates have been demonstrated by, for example, Advanced Scientific Concepts (Roger and Howard) as well as other companies. This type of 3D CVS based on using an array of detectors to simultaneously measure the times of flight of portions of a laser pulse reflected from multiple points in a scene is also known as flash LIDAR.

Range gating, a lower cost approach for automotive applications, involves indirectly measuring the time-of-flight by integrating reflected light pulses using two integration time windows (Medina et al., 2006; Gokturk et al., 2004) (It is much easier to generate wide pulses with well-defined transitions than it is to precisely measure the delays of narrow pulses with sub-nanosecond accuracy). For the first integration window, a time period equal in length to the optical pulse is used. The reflected light is integrated as soon as the pulse is emitted. If the light imaged on a pixel is reflected from a nearby object patch, most of the reflected light pulse occurs inside the window and the integrated signal is large. If the object patch is further away, some of the reflected light will be received after the window closes and the integrated signal will be smaller. The second integration window begins after the first window ends. Due to the delay between windows, the second window integrated signal will increase with distance of the object patch because the time overlap of the return pulse with the window will increase. By taking the difference between the two window signals and normalising by their sum, the range can be measured and the effects of different object reflectivities are compensated. In the range gating method, the maximum measurable range is limited by the pulse width. Pulse returns from a distant object that take longer than a measurement cycle to arrive can result in range ambiguity. Range gating can be used to suppress objects outside a specified distance range, which also helps to see through scattering media such as fog. The effects of background illumination can be compensated by performing a second calibration measurement with the illumination turned off. The second calibration pulse also provides a conventional image of the scene that is perfectly registered with the range image. Fusing the two images results in a 3D texture-mapped representation of the scene that is very useful for vision applications.

TriDiCam (http://www.tridicam.net/), D-Imager (http://pewa.panasonic.com/components/built-in-sensors/3d-image-sensors/d-imager/), DepthSense (http://www.softkinetic.com/AboutUs/VisionandMission.aspx), 3DV (Iddan and G. Yahav) and Canesta (http://venturebeat.com/2009/10/21/canesta-raises-16m-for-chips-that-sense-3-d-motion/) are examples of companies that have developed 3D CVS cameras based on range-gating. 3DV and Canesta were recently acquired by Microsoft to support its 3D gesture-based gaming interfaces. Fotonic (http://www.fotonic.com/content/Products/Default.aspx) has developed range-gated 3D cameras powered by the Canesta 3D imaging chip. Canesta has also developed a virtual keyboard chipset. It consists of an LED projector that images a keyboard on any flat surface. The operator 'presses' keys on the keyboard image and a second LED emits illuminating light pulses. The positions of the fingers are analysed using the 3D CVS camera to determine which virtual key has been pressed. The camera module includes the CanestaVision detector chip, lens, light source and associated electronic support circuitry to return frames of 3D depth data. Such low cost 3D imaging could be a breakthrough technology for automotive vision applications, since it could be used for robust segmentation and recognition of objects using distance and 3D shape information. The system would have to be re-engineered for automotive applications. For example, much brighter pulses and longer integration windows would be needed for outdoor applications at long ranges.

In the RF-modulated approach for 3D CVS, the outgoing beam is modulated with an RF carrier. The phase shift of the carrier is then measured on the receive side. The RF carrier wavelength determines the maximum range that can be measured without ambiguity. The range accuracy of the approach is reduced for larger ranges, since the phase must then be measured with high accuracy. Examples of this approach are the PMD [vision] CamCube by PMD Technologies (http://www.pmdtec.com/fileadmin/pmdtec/downloads/documentation/datasheet camcu be.pdf) and the SwissRanger 4000 by Mesa Imaging (http://www.mesa-imaging.ch/prodview4k.php). The PMD camera uses a photonic mixer device at each pixel, which enables fast optical sensing and demodulation. Each PMD sensor contains two modulation gates which control the lateral flow of charges. A reference modulation signal connected to the gates causes photo-induced charges to flow left or right. The return light from the illuminated object is also modulated with the reference signal, but delayed in phase due to the range of the object. By measuring the difference of voltages of the two output nodes, the phase shift between the reference signal and the return signal can be measured, which in turn is proportional to the object range. A system for pedestrian detection was developed by PMD with a measurement range of 10 m using a one watt illumination source. The SwissRanger 4000 uses a similar approach and also has a maximum range of 10 m. It is designed for indoor use and cannot be used in direct sunlight. A potential limitation of RF modulated approaches for automotive applications is the relatively high optical illumination levels needed to achieve reasonable ranges in outdoor settings for ASDAS applications. Range-gated methods have an advantage over RF-modulated approaches due to the use of illumination pulses with high peak but low average power, which enables high SNR using compact and low-cost LEDs. Another disadvantage of RF-modulated methods is the lack of time-gating for extraction of light from specified range bins, which is useful for eliminating multiple return signals caused by multiple reflections or foreground objects. Since these are fundamental limitations, it is likely that range-gated 3D CVS will maintain its advantages over RF-modulated approaches for automotive applications.

2.1.2.4 Structured light 3D CVS

Another category of 3D CVS determines the 3D structure of a scene using projection of patterns or structured illumination onto the scene. By analysing the distortions in a known coded light pattern projected onto a 3D scene, a reconstruction of the 3D structure can be performed. Unlike time-of-flight-based 3D CVS, which measures the range at each pixel directly, structured-light-based 3D CVS measures the range indirectly through post-processing of the detected information. An example of a 3D CVS sensor product based on this principle is the PrimeSensor™ reference design from PrimeSense (http://www.primesense.com) which is used in the Kinect 3D gesture recognition-based game control system from Microsoft. While such systems work well for indoor control of video games, using them for outdoor automotive applications is problematic due to their limited range and inability to handle sunlight illumination.

2.1.3 Computer vision algorithms

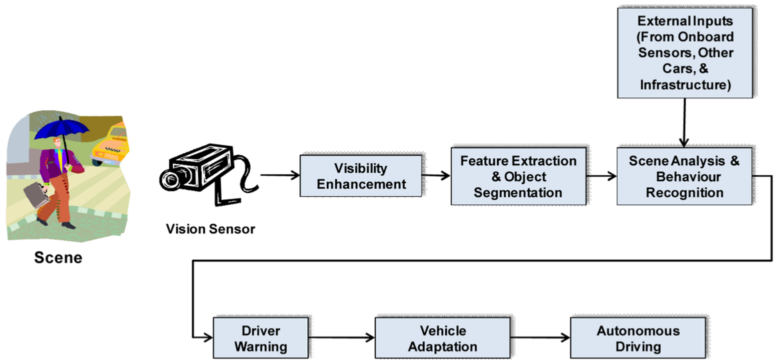
Computer vision algorithms are a very active area of current research due to the richness of visual information and the high complexity of the visual scene understanding problem. The continued development of new vision algorithms in addition to increases in available computational resources will result in not only improved vision-based object recognition and vehicle guidance, but also greatly improved image sensing systems. These improvements are being driven to some degree by automotive applications, but are mostly being driven by the digital camera/smart phone consumer, computer graphics and commercial/defence surveillance and security markets. Vision algorithms for ASDAS applications can be divided into two groups:

1. visibility algorithms for enhancing the performance of vision sensors or adding new imaging functionality
2. recognition algorithms for scene understanding.

A high-level flow chart showing how vision fits into the ASDAS application hierarchy is shown in Figure 2. Robust computer vision (or image processing) algorithms can extract pertinent scene information needed by a vehicle active safety system for collision avoidance or mitigation. Visibility algorithms are first applied to imaging data from sensors to enhance the visibility of vehicle scenes. Recognition algorithms then perform scene understanding analysis by conducting feature extraction and object segmentation to recognise road hazards and possible impending collision for driver warning or assistance.

A large variety of visibility enhancement algorithms are currently under development at both universities and commercial companies.[2] An active area of research is the enhancement of situation awareness by greatly increasing the field- of view using omnivision cameras and real-time image mosaicing. Omnivision systems are now commercially available (although at relatively high cost) and can provide real-time views over almost the entire sphere (e.g., Ladybug spherical digital camera from Point Grey Research). Some of these systems use special optics and a single camera together with image dewarping algorithms to generate a low resolution omnivision view at relatively low cost in a relatively bulky package. Other systems use multiple cameras pointing in different directions. The separate video streams are then combined into a single high resolution omnivision view using warping and mosaicing algorithms. This approach generates a high-resolution omnivision view using a relatively small package, but at a higher cost, since up to 6 cameras are used. In 2003, the first real-time algorithms were demonstrated for constructing 3D views of scenes from multiple 2D views using uncalibrated cameras in arbitrary positions (David, 2003). Unlike existing stereo camera systems, these systems can utilise multiple cameras that are widely separated and observe the scene from very different viewpoints. Full 3D models of the scene can be constructed without prior knowledge of the cameras' relative positions or optical parameters.

Figure 2 Application levels of vision sensors and algorithms for ASDASs (see online version for colours)



Combining multiple views can be used to not only increase the field of view and provide 3D scene information, but also to improve the image resolution (super-resolution) (Elad and Feuer, 1999). Sub-pixel resolution can be achieved, although the registration and computational requirements are high for real-time operation. Super-resolution will be useful for detecting objects at large distances without telephoto zoom lenses.

In the future, as flexible large area organic LED (OLED) displays become practical, image-warping algorithms and omnivision cameras could be used to enhance driver situation awareness by applying OLED displays to blind spots in the car and displaying what the driver would see if the blind spots were not there. In other words, the outside scene could be warped and shown on conformal displays fitted to the blind spots in the vehicle interior, resulting in a natural 360^{o} convertible-like view for the driver of a sedan, which allows him or her to 'see through' opaque parts of the cabin. The driver's view would consist of a combination of real-world views through the glass windows and virtual views through the blind spots. The virtual views would not have depth information but, nevertheless, would be useful for increased situational awareness. Alternatively, as head-mounted displays become smaller, cheaper and more accepted by the public, views from stereo wide-angle cameras could be mapped to the driver's point of view and displayed as virtual views on the driver's goggles. This is a long term possibility, as many advances are first necessary in processing power, image update rates, head-mounted displays, image registration, head tracking and camera technology. Furthermore, while such systems are under active development for military applications, the acceptability of such systems by the consumer automotive market is to be seen. The technology drivers are the gaming, training and mobile information markets.

The other main application area of computer vision algorithms for ASDAS is in enabling the vehicle to understand its environment and respond to it. Vision-based scene understanding includes object detection, recognition, measurement, tracking and behaviour analysis. System applications of these algorithms include outward-looking ASDAS applications such as pre-crash sensing, collision avoidance/mitigation, blind spot monitoring, backup warning, automatic parking, adaptive cruise control around curves and lane following, as well as inward-looking ones such as intelligent airbag deployment, distracted driver monitoring and security. Until recently, most vision research groups have concentrated on processing 2D images from single cameras or have researched and implemented systems that add range information to the 2D images using radar or stereo cameras with short baselines. An active research area is to incorporate the 3D nature of objects in the recognition process. Another emerging trend is to utilise motion information in video and recognise objects using their spatio-temporal properties. In the coming decade, vision systems will reliably recognise not only objects in a scene, but also their behaviours. It is beyond the scope of this study to describe the many vision algorithms in this vibrant and rapidly advancing field. We will only mention current and anticipated general trends in vision ASDAS applications.

Vision systems have been demonstrated for several safety applications. Lane following and lane departure detection have been demonstrated by several OEMs, suppliers and research organisations and are being deployed in production. Presently, a commercial lane departure warning product is available in most car markets, including the US market. Next generation smart airbag sensors based on vision have been demonstrated by several organisations. These systems are useful for recognising the vehicle occupants and their positions relative to the airbag. They can also be used for security applications. Sensing of objects outside the vehicle, such as other cars, pedestrians and signs is an important capability for pedestrian protection, pre-crash sensing and collision avoidance and mitigation, as well as for driver alerts such as warning of approaching cars and stop signs. Vision-based object sensing is in various stages of development for different object types. For example, detecting cars and tracking them on the road is a capability that has been developed by several organisations and is now being deployed. Pedestrian detection, on the other hand, is a more difficult problem due to the non-rigid and variable shape of humans. However, much progress has been made and pedestrian detection systems for collision avoidance/mitigation and backup warning have been demonstrated.

Active safety and driver assistant vision applications will continue to benefit for the foreseeable future from the work being done on computer vision algorithms for other applications in the defence (force protection, automatic target recognition), homeland security (surveillance) and commercial (entertainment, security, computer graphics) markets. The proliferation of surveillance cameras and requirements for increased security has resulted in increased research in recognising, fingerprinting and tracking objects across disjoint views using multiple cameras. Methods for creating a single coherent view by combining the outputs of multiple cameras are also an active area of research and viable systems have been demonstrated. Object recognition using 3D models is also being pursued. Methods for automatically creating 3D models of objects using uncalibrated multiple cameras is an interesting and active area that could also eventually benefit the active safety field as more cameras are mounted on cars.

A common sensing requirement for all of the above automotive applications is large inter- and intra-scene dynamic range capability. The vision systems must operate under both bright sunlight and low-light night-time conditions, a range that the human eye can for the most part easily accommodate, but which is challenging for imaging sensors. It has been estimated that an intra-scene dynamic range of 120 db is needed to handle challenging scenes such as entering a dark tunnel or parking structure on a sunny day. As we will see below, CVS sensors have been recently developed that can meet this challenge.

2.1.4 Vision sensor architectures for high dynamic range

CMOS vision sensors have architecture flexibility that allows in-pixel signal processing for dynamic range enhancement, up to 150 dB, to be achieved using various active-pixel circuitries and operating modes without sacrificing frame rates or increasing cost, although SNR can be reduced. Several such active pixel techniques for achieving high dynamic range in CVS have been implemented (El Gamal; Doswald et al., 2000). These techniques include well capacity adjustment, spatially-varying exposure, measuring time to saturation, logarithmic response, local adaptation and intra-scene multi-slope operating modes. Currently, the most successful approach in the automotive market for maximising intra-scene dynamic range is the use of multiple slope operation modes in the same image, as in the LUPA series of image sensors from Cypress (www.cypress.com/go/imagesensors) or the DR-Pix technology from Aptina Imaging (http://www.aptina.com/products/technology/DR-Pix_WhitePaper.pdf).

It is beyond the scope of this paper to describe each of the above CVS dynamic range enhancement mechanisms in detail, but we can form some general conclusions. In terms of theoretical performance, capturing multiple frames using multiple neutral density filters is superior for imaging purposes because of its high dynamic range, scalability to higher dynamic range through additional stages and linearity, but it requires a high speed non-destructive readout sensor as well as expensive external hardware and external memory for implementation. In addition, it results in a reduced frame rate. A more practical solution is the use of active pixels to enhance the imaging properties of the sensor, such as dynamic range, random access and to sense more scene information by adding dimensions such as wavelength and range. By performing time-gated imaging, active pixels can be used to not only increase the dynamic range, but also measure range and form a 3D representation of the scene, as described in Section 2.1.2. Practical automotive CVS products utilise time-to-saturation, logarithmic, or local adaptation active-pixel based approaches to achieve high dynamic ranges at reasonable cost.

2.1.5 Cost/performance of vision sensor technologies

New applications in digital imaging (digital cameras, smart phones, digital cinema, tablets, etc.) have created a demand for solid state vision sensors which are inexpensive, compactly packaged, offer area-of-interest or random readout and allow flexible architectures while maintaining an acceptable level of imaging performance. These requirements cannot be met by CCD technologies and have resulted in accelerated development of CVS technologies in the past twenty years. Automotive users of CVS can benefit from the huge investment and research funds being expended by the digital imaging industry.

Digital imaging has grown into a fast-growing multi-billion dollar consumer electronics business that is being driven by large non-automotive markets with short product refresh cycles. Low cost, high performance CVSs appear regularly in new smart phone, tablet and digital camera products on a monthly basis. Major suppliers such as Cypress, Aptina Imaging, Melexis and Omnivision, as well as other OEMs, all have CVS product lines that continue the quest for low cost, high resolution, high dynamic range and high frame rate CVS devices. For example, Melexis offers a logarithmic response CVS for automotive applications with 1024×512 resolution, 60 frames per sec and 154 db dynamic range (http://www.melexis.com/Sensor-ICs-Infrared-and-Optical/Optical-sensing/Avocet–High-Dynamic-Range-CMOS-Image-Sensor-696.aspx). Aptina Imaging (http://www.aptina.com/products/image_sensors/) offers a dual-slope automotive CVS sensor with 1.2 megapixels, 45 frames per second and 115 db dynamic range. A number of vision sensor suppliers are also pushing the state-of-the art on high-end CVS for high resolution applications. For example, Aptina Imaging offers a CVS sensor with 16 megapixels and 11 frames per second capture rate. Omnivision (http://www.ovt.com/products/) offers a 15 megapixel sensor that can operate at 15 frames per second in full resolution or 60 frames per second at 1080 p HD resolution with pixel binning.

Many of the companies developing 3D CVS, such as the Canesta and 3DV divisions of Microsoft, are not focused on the automotive market. Other organisations are defence-oriented, such as Lincoln Labs, which performed the first test flight in 2003 of an airborne 3-D laser imager that utilises a pulsed infrared laser and a solid-state imaging array to form 3-D images of obscured objects through foliage. Advanced Scientific Concepts has also developed such flash LIDAR camera systems using InGaAs avalanche photodiode arrays, including the 128×128 TigerEyeTM camera (http://advancedscientificconcepts.com/products/tigereye.html).

All of the major car manufacturers and suppliers have recognised the importance of vision-based systems in future ASDAS applications and are doing research or product development on such systems. The focus now is primarily on warning systems, for example, using CVS to detect objects in a driver's blind spot during turns and triggering warnings. Automotive OEMs have developed CVS systems for tracking lane position and warning drivers against drifting into other lanes. Vehicle and pedestrian detection systems are now appearing on high end vehicle models such as the 2012 Volvo S60, which uses a combination of radar and IR CVS. In addition, CVS systems are used to track eyelid movements for detecting drowsy drivers. Such systems are also useful for generating inputs for systems that track high-stress driving conditions and block nonessential information while the driver is pre-occupied (MIT Technology Review).

2.1.6 Vision sensor technology change in the near-, mid- and long-term

Regarding future trends for vision sensors, huge investments will continue to be made in the technology by players in the digital imaging market that will result in continued improvements in performance and price. Such rapid progress combined with continued advancements in low cost processing chips, such as digital signal processing (DSP) chips and field programmable gate arrays (FPGAs) and advancements in vision algorithms will further enable the deployment of ASDAS vision systems in automobiles. The required hardware advancements will not be driven by the relatively long product cycle time of the automotive industry, but by the much shorter cycle times of the very substantial electronic digital imaging industry. On a related note, synergies have developed between digital special effects and graphics tools for the entertainment industry and computer vision algorithms. For example, an area of intersection and mutual interest between the computer graphics and computer vision communities is the representation and tracking of 3D objects in a 3D world using multiple camera viewpoints (see section on vision algorithms). This confluence of development efforts by multiple large fast-moving commercial industries will accelerate the development of computer vision technology for ASDAS applications.

In terms of smart vision sensors, a flurry of papers appeared in the ten years after publication of Mahowald and Mead's seminal silicon retina chip in 1988. The motivation for these initial 'smart pixel' chips was emulation of specific aspects of biological vision systems as opposed to practical applications. While research continues, no high resolution smart pixel sensor has yet been demonstrated that is practical for automotive applications, offers a variety of programmable processing options and has performance superior to more conventional digital processing of sensor images. This is due in large part to the fact that when imaging and processing functions are combined in the same physical pixel structure, it becomes difficult to jointly optimise both functions. In addition, the incorporation of circuitry at each pixel reduces the fill factor or fractional photosensitive area, thereby reducing the sensitivity of the sensor. The more conventional approach of physically separating the imaging and processing functions allows each to be optimised separately and results in more development resources applied to each function because of the wider range of potential applications. Other advantages of this separation are the greater flexibility and programmability of the sensor architecture. Therefore, we do not believe that in the near future active pixel structures which perform spatial processing directly at the detection site will form the basis for practical smart vision sensors. Vision processing circuitry will remain separated from the sensor pixels, although it may be on the same chip. Another potentially interesting approach is to put the processing circuitry underneath the sensor pixels using thin-film on ASIC or another hybrid technique that forms 3D structures from multiple chips. In the future, developments in visibility algorithms for vision-based situation awareness will also greatly improve the scene-sensing capabilities, making them more suitable for active safety and driver convenience features application

Our assessment of trends in vision sensor technologies in the near-, mid-and long-term is summarised below.

Near-term: Continued rapid improvements in CVS cost and performance will occur, as well as continued improvements in ASDAS vision algorithms, driven by other applications such as surveillance and smart phones. Systems will be developed for object detection and recognition for ASDAS, both outward-looking (collision avoidance, intelligent cruise control around curves, integration of vision with telematics and navigation systems including GPS and digital maps, robust lane following) and inward-looking (smart airbags, security, driver gaze monitoring).

Mid-term: 3D CVS and LED headlights for 3D scene sensing, real-time synthesis of 3D models from multiple viewpoints and 3D vision sensors and algorithms will be developed.

Long-term: New technologies will be developed for smart pixel imagers based on hybrid 3D construction methods, enhanced driver vision using algorithms for displaying warped imagery on see-through wide-area flexible displays and active safety systems based on cooperation between onboard and infrastructure cameras.

2.2 Infrared (IR) imaging sensors

Near-infrared collision avoidance systems have demonstrated the advantages of high precision, small size and low cost when compared to millimetre wave-radar systems. However, in comparison to the millimetre wave-radar system, the near-infrared system's performance degrades in inclement weather. This section discusses IR sensors, including photo-sensor arrays, MEMS-based bolometers and THz sensors. The sensors can be configured either as an array of passive devices or as a component in an actively illuminated scene. In the latter case, fibre lasers and diode lasers (1.5 μm), Quantum Cascade Lasers (QCL) (5 μm to > 10 μm in the mid-IR region) serve as potential IR sources that can produce enhanced visibility under adverse visibility conditions, including extreme fog, rain and black ice. Other classes of IR sources include nanoparticle-based and nanotube-based devices as well as THz devices. Although still in the development phase, these components may find many applications in the mid- to long-term for enhanced visibility, imaging and safety.

2.2.1 Functionality

IR sensors collect thermal-induced photons from an object and convert them into photoelectronics for an electrical signal output. The basic functions of IR sensors in ASDAS include occupant detection and imaging within a vehicle (passengers, items or children within the trunk) and external to a vehicle, with spatial as well as spectral resolution sufficient to distinguish humans and animals from inanimate objects (such as night vision systems). Near and far IR sensors can operate effectively over the typical ranges of interest for ASDAS of less than 1 metre to greater than 100 metres for most object brightness and ambient illumination conditions.

Applications of IR sensors for ASDAS include facial imaging of a driver combined with gaze detection methods for driver alertness sensing and warning; day and night object detection in passively and actively illuminated scenes for collision avoidance (vehicles, animals, pedestrians, etc.); enhanced inclement weather viewing (fog, snow, etc.); road sign driver alerts (these signs could be permanent as well as temporary and passive or active); and road condition sensing for suspension control and antiskid feedback (detection of potholes, boulders, black ice, etc.). By sensing the road conditions ahead of the vehicle, predictive road condition sensing can be coupled into the suspension control system to optimise the shock absorber settings for improved vehicle ride and control.

2.2.2 IR sensor types

Multiple types of near IR and far IR sensors can be matched to specific ASDAS applications. Optical sensing devices operating in near IR and far IR ranges include semiconductor photodiodes, avalanche photo-diodes, quantum well devices including MEMS-based bolometers, quantum cascade detectors and Quantum Well Infrared Photodetectors (QWIPS) (Choi, 1997). The selection will be guided by the requirements for spatial resolution, dynamic range, response time, sensitivity and the wavelengths to be detected. Spatial attributes of sensors include single sensors, linear arrays and multi-pixel Focal Plane Array (FPA) imaging sensors. Spectral attributes of the sensor design can include several different narrowband devices that are combined laterally or longitudinally for multi-wavelength response at each spatial pixel. Sensor arrays can operate at video frame rates to form a video image just like a silicon vision sensor operating in the visible range.

The state-of-the-art in IR image processing has been developed primarily for military applications, where accurate object (vehicle and human) detection, tracking and recognition have been demonstrated. IR imagery has also been combined with visible imagery to produce enhanced imagery that enables seeing through smoke or bad weather. IR processing for active safety applications has been limited because of the lack of low cost IR imaging sensors.

2.2.3 Spectral range

The spectral range of IR sensors can be broken up into bands which can be broadly divided in the following ranges; near IR (1 μm; eye-safe > 1.5 μm) to mid-IR (3–10 μm) to far-IR and THz (100 μm and beyond). There are a number of semiconductor IR sensors operating from the near-IR to the far-IR range. The spectral response of semiconductor IR sensors is determined by the device material system, which include various II-V or II-VI semiconductors such as GaAs/GaAlAs (0.8–0.9 μm), InP/InGaAsP (1.2–1.6 μm), PbSe (2–4 μm), InSb (3–5 μm), HgCdTe (8–10 μm). Narrowband IR sensors (~ 1% BW) operating in ~ 1–10 nm spectral ranges include quantum well devices and avalanche photo-diodes. Broadband devices (50% BW) include compact, low-cost/pixel MEMS-based bolometers.

For optimum performance in vehicle active safety systems, the choice of IR spectral band of the IR sensor should be within one of the atmospheric transmission windows in the IR region to reduce signal loss (due to attenuation). This is the primary reason behind selecting the mid-IR band for the IR sensors used in ASDASs – because the wavelength range from 8–12 μm is within an atmospheric transmission window. The transmission as a function of wavelength for the atmosphere is shown in Figure 2.3. One can see that there are three regions where the attenuation is significantly reduced.

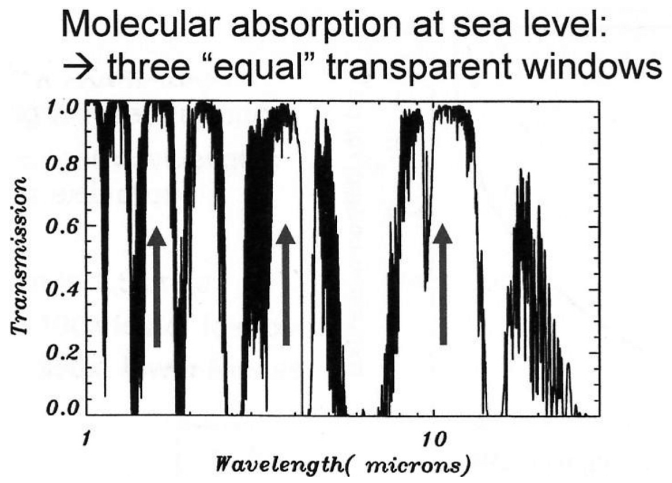
2.2.4 System architectures and implementations

IR sensing implementations for ASDASs can be divided into systems that use passive and active illumination methods. In passive imaging, the image of the object or scene is captured using naturally occurring illumination in reflection or the use of self generation of IR (thermal) radiation from the object. In active imaging, the illumination is generated by IR sources such as LEDs, fibre lasers, laser diodes, QCL (Gmachil et al., 2003; Capasso et al., 2002) or THz illuminators (Weide, 2003). The advantage of active illumination is that the illumination wavelength, power and temporal properties can be controlled. The active illuminators can be integrated into each vehicle or can be added to existing road light fixtures (infrastructure, timers and prime power presently in place), or both.

2.2.5 Passive IR sensors

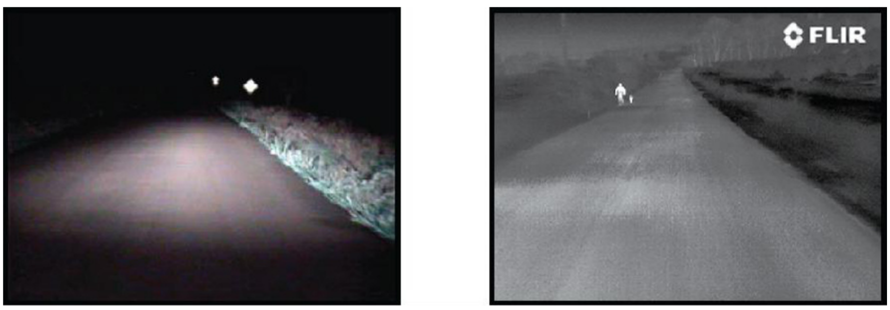
Passive IR sensors are further categorised into cooled and uncooled sensors. Uncooled sensors include bolometers, which are operated at room temperature and are the primary passive sensors used in automotive applications. Bolometers use vanadium oxide (or alternatively, amorphous silicon) as a heat detector. Infrared radiation strikes the vanadium oxide, heats the detector and thereby changes its electrical resistance. The change in electrical resistance in the vanadium oxide pixel elements in a sensor array is read by a Si readout integrated circuit (ROIC) to generate the image. These sensors are also called thermal sensors, as they utilise the infrared radiation emitted by the object, as opposed to the ambient illumination, to generate imagery. Bolometers are monolithic devices where the detector elements are fabricated directly atop the ROIC, resulting in enhanced manufacturability and cost reduction associated with a silicon-like manufacturing process.

Figure 3 Atmosphere transmission over 1–15 μm range. Arrows indicate three windows with high transmission



Bolometer-based thermal sensors let drivers see people, obstacles and other hazards in total darkness and through dust and smoke. Additionally, bolometers enable a driver to see about four times farther away at night than with headlight illumination. An example of the benefits offered by a bolometer is described in a brochure of a camera manufacturer, FLIR and illustrated below.

Figure 4 Example images showing the benefit of a bolometer IR sensor. Conventional view using no sensor assistance (left) and enhanced detail seen using a bolometer (right). Pictures reproduced from FLIR brochure on PathFindIR thermal night vision system, www.flir.com (see online version for colours)



2.2.6 Active IR sensors

Passive sensors provide assistance by enhancing the view well over that possible with the naked eye using ambient illumination. LIDAR sensors, on the other hand, are referred to as active sensors, as they utilise controlled laser pulses and a timing signal to acquire range information. Range measurements are made through active illumination and measurement of the delay in arrival of the reflected return signal (i.e., time of flight). The range information provides navigation assistance for adaptive cruise control, collision avoidance, lane change, etc.

The sensor which detects the return signal can be a single element detector or a 2-dimensional imaging array. Single element detectors can provide range (distance) information, but provide limited information about the dimensions and details of a nearby object. On the other hand two-dimensional imaging arrays, especially when combined as a suite of detectors to cover a wide field of view, can generate accurate 3D images of neighbours, providing useful depth information. This level of detail can be utilised to determine position and relative motion, to identify obstacles and to provide navigation assistance while simultaneously minimising false alarm. The detailed real-time range information together with object identification potential has the capability to alert a driver a few hundred milliseconds before a potential collision. This advance warning potentially allows for the driver or an autonomous vehicle to take appropriate manoeuvres, such as braking or lane change to avoid the obstacle (Lindner and Wanielik, 2009; Pananurak et al., 2009).

Advanced prototype LIDAR systems have been used to evaluate the full potential of theses sensors at the prototype level. McBride et al. reported on the need for a redundant set of sensors for autonomous vehicles and the utility of a Velodyne HDL-64 LIDAR sensor with a 360-degree field of view (McBride et al., 2008; Schwarz, 2010). The HDL-64 utilises a near-infrared laser operating at 905 nm and 64 lasers and detectors. While this system demonstrates the utility of a 360 degree field of view sensor, it is not practical for commercial use in automobiles due to its bulk and high cost (similarly, Velodyne's smaller HDL-32 LIDAR sensor with 32 beams is currently available in the market).

Practical systems can use a very low-power 905 nm laser which can be detected using a CMOS imager. Alternatively, the illuminator can be a 1.5 µm laser, which is available commercially for telecom applications. True eye safe operation, however, requires the use of InGaAs-based short-wave infrared detector arrays, which will drive up the cost of such a system. While mechanically-scanned LIDAR sensors offer significant navigation assistance and 3D obstacle avoidance which can enhance safety, the cost of such a system is presently high for use in commercially produced automobiles. Advances in manufacturing and fabrication processes which leverage the volume needed for automotive applications can potentially drive down the cost of these systems.

2.2.7 Cost/performance of IR sensor technologies

Many photonics manufacturing companies currently address the IR component needs for both aerospace and telecommunication systems. This photonics manufacturing base can make the cost and performance of IR sensors attractive and practical for the automotive industry, for use as OEM devices and subsystems. High-volume MEMS-based technologies (e.g., for bolometer arrays) can be practical, especially given recent advances in high-yield, HD projector MEMS-based spatial light modulators, which are now standard items for consumer and cinema projection systems (Hardin, 2003). Common sensor platforms (shared aperture) and common algorithm requirements of multiple sensor packages can result in a cost-effective processor package.

Current users for eye-safe photonics devices and systems include the telecommunication, surveillance and aerospace industries. Many telecommunication equipment suppliers, such as Lucent, NEC, Hitachi and Mitsubishi, offer near IR (1.5 μm) eye-safe semiconductor sources and detectors such as InGaAsP diode lasers, fibre lasers and InP detectors. Mid-IR (3–5 μm) and far-IR (8–10 μm) detectors are widely used by the surveillance and aerospace industries for object/target detection.

GM, Jaguar, Daimler and Chrysler are current users of ASDAS IR sensors. GM offered an infrared night-vision system in the 2000 Cadillac DeVille using an IR imager developed by Raytheon Commercial Electronics (Dallas, TX). The system utilises a grill-mounted IR video camera and a realtime, upward-facing display that projects an image on the lower section of the windshield. This night vision technology allows drivers to see as much as five times as far as they can with normal headlamps. The IR video camera uses optics to focus infrared radiation onto a 1-inch un-cooled FPA detector to form a thermal image of the object. Warm objects (including deer and cars parked on the roadside) appear brighter than background or other cold objects such as street signs, providing added warning about potential hazards.

2.2.8 IR sensor technology change in the near-, mid- and long-term

In the past, mid-IR systems were not considered to be viable systems due to the lack of relatively inexpensive and reliable sources and detectors. Furthermore, there was some controversy about the operational effectiveness of mid-IR in adverse weather. However, the controversy has been resolved by the recent demonstration of excellent free space optical transmission in near-zero visibility weather conditions conducted by researchers from Stevens Institute Technology and Lucent Technologies (Hardin, 2003). They compared the 0.85 μm near-IR system with a mid-IR 8.1 μm system side-by-side and found that the mid-IR is far superior to the near-IR system. They predicted that with the rapidly continuous progress in source and detector technology, the mid-IR can be up to 100 times (and possibly even better with further improvement in optics and detectors) better than a near-IR system.

This impressive field demonstration of the mid-IR system plus the rapid progress in semiconductor lasers and detectors technology may favourably change the prospect for mid-IR systems. Among the different types of mid-IR sources, QCLs based on the III-V compound semiconductor material system, are a particularly promising coherent source for the 4.5–15 μm spectral region. A continuous wave (CW) QCL operated at room temperature with output up to 17 mw at 9.1 μm has been demonstrated (Hofstetter et al., 2002). In addition, a pulsed QCL emitting at 10 μm operated at a temperature of up to 95°C was also reported (Baker et al., 2002). Similar progress can also be found in the III-V based mid-IR detector technology area. A photodiode based on InSb/GaInSb type-II superlattices has demonstrated detectivity between 8–12 μm in the 10^{11}–10^{12} cmHz$^{1/2}$/W range (Fuchs et al., 2002). With such significant progress in the source and detector technology, we expect that a low cost active collision avoidance system based on mid-IR technology can become a reality in 6–9 years.

Rapid advances in IR image processing algorithms for ASDASs will occur because of the recent deployment and availability of IR image sensors from automotive OEMs. In the near future, algorithms for lane recognition, road curvature estimation and object detection/

tracking/classification that exploit IR imagery will be developed. In addition, algorithms will be developed that fuse IR imaging sensors with radar or vision sensors. In the next 5 to 10 years' time frame, IR processing algorithms will continue to be refined to take advantage of the increased sensitivity and resolution of IR imaging sensors. If the cost of IR imaging sensors can be sufficiently reduced, then stereo IR imaging sensors and algorithms to exploit 3D information may also become commercially available.

2.3 Hyperspectral imaging systems

Hyperspectral imaging sensors employ a collection of detector arrays and sensors to perform multi-dimensional spatial (or wavelength) mapping of a given scene to enable collection of high-resolution images for feature extraction. The number of different wavelengths used to create the images can be as low as 6 to as high as 300. While an active-illumination-based system must generate and then transmit its own set of wavelengths towards a given object, a passive-illumination-based hyperspectral system simply captures the reflected ambient illumination along with any wavelengths transmitted by the given object.

Currently, a human driver relies largely on various visual inputs as the basis for his driving decisions. For certain safety applications such as the accident avoidance application, a multi-dimensional electronic image can be enhanced using hyperspectral imaging and processing to include accident avoidance information along with optional driver advice by utilising (range-Doppler) optical- and acoustic-returns from various proximal objects and vehicles.

2.3.1 Functionality

A hyperspectral image is typically represented as a 'hyperspectral data cube' with spatial and spectral axes. The spectral axes can include optical, infra-red and RF coordinates. Since different objects reflect and absorb different wavelengths in differing amounts, one can use this fact to 'visualise' different information in a given scene, because each object in the scene would have a different spectral signature. For example, the IR signature emitted by a pedestrian is significantly different from that of a tree. Also, signatures of most man-made objects, such as painted metal, are also very different from those of naturally occurring objects. By taking advantage of differences in spectral signatures, a hyperspectral system can identify objects that may be partially obscured or may be at a distance farther than the range of single-spectral-band detectors.

An illustration of hyperspectral data taken in the visible and IR range is shown in Figure 4. This data is from the Airborne Visible and IR Imaging Spectrometer (AVIRIS) project. The main objective of the AVIRIS project is to identify, measure and monitor constituents of the Earth's surface and atmosphere based on molecular absorption and particle scattering signatures. The data was taken using a NASA instrument built and operated by HPL Moffet Field, CA. The hyperspectral optical sensor captures spectral radiance in 224 contiguous spectral bands with wavelengths from 0.4 to 2.5 micrometres.

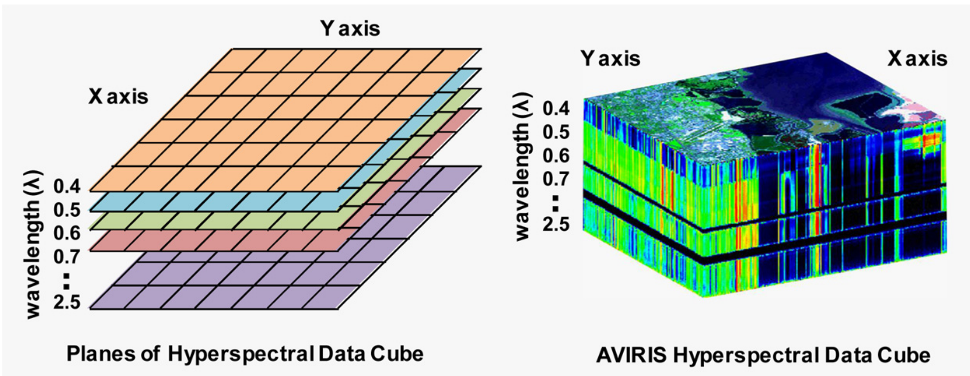
2.3.2 Spectral range and resolution

The spectral range and resolution of hyperspectral sensors are determined by the type of EM sensor, sensor design parameters (field of view, sensitivity, dynamic range), data-bus lines (internal, external), cross talk, clock rate, signal-to-noise-ratio considerations and total data handling capacity of the pre-processors and post-processors.

2.3.3 Applications

The ability to provide enhanced situational awareness and viewing during adverse environmental conditions is highly desirable and may become an integral part of future ASDASs. During inclement weather (snow, heavy rain and low-visibility fog), information in the visible spectrum, taken alone, is often insufficient to render a high-resolution image that can accurately reveal nearby objects and obscurations (pedestrians, animals, cross traffic) to the driver of a vehicle. However, information in other spectral bands (such as infrared, ultraviolet, mm-waves and tera-hertz waves) can be combined to generate a high-resolution image of the same scene with a higher degree of detail, clarity and accuracy. A number of proof-of-concept simulations as well as demonstrations that combine images from visible, near-infrared, short-wave-infrared, mid-wave-infrared and long-wave-infrared bands are well documented in the literature. For example, in Tao et al. (2005), the authors discuss fusion of images from the visible and long-wave-infrared sensors to enable enhanced viewing in poor lighting conditions. Along similar lines, in Williams et al. (2008), the authors discuss experimenting with a forward-looking, multispectral system mounted on an all-terrain-vehicle and describe an algorithm development tool that can be used to fuse images from the visible, near-, short- and long-wave-infrared sensors of the system.

Figure 5 Hyperspectral data from Airborne Visible and IR Imaging Spectrometer (AVIRIS) (see online version for colours)



BAE Systems recently demonstrated its advanced night vision imaging system improved head-up display (ANVIS IHUD) that allows airborne pilots to maintain exterior situational awareness during darkness, inclement weather and other visibility-limiting conditions. A number of companies are also developing compact, light-weight hyperspectral sensors capable of real-time image fusion for spectral tagging, target material tracking and surveillance applications (Nebiker et al., 2008).

Some of the other promising or well developed fields of application of hyperspectral imaging and processing related technologies are geologic mapping, environmental monitoring, vegetation analysis, atmospheric characterisation and climate research, biological and chemical detection, target material detection and discrimination, target material recognition and tracking and long-range reconnaissance and surveillance. A detailed survey of various hyperspectral imaging technologies and imagers used in air-borne, space-borne, or ground-based systems is available in Technical Report TR-SET-065-P3 (2007).

2.3.4 System architectures and implementations

Hyperspectral sensors are typically designed to respond to reflected solar light in the visible-to-mid-infrared spectral bands. Different objects have different 'fingerprints' across the electromagnetic spectrum and hyperspectral sensors capture these 'fingerprints' (commonly referred to as spectral signatures) in the form of spectral reflectance values. Many of the popular target material detection and recognition algorithms rely on matching spectral signatures of scanned objects to pre-classified spectral signatures of various known objects. By using a reference library database of spectral signatures, an algorithm can quickly calculate the correlation between spectral signatures of various known objects in the library and the spectral signature of the scanned object to detect the presence of the target material in the captured hyperspectral image.

The data can be captured in several different configurations. A two-dimensional representation of a scene can be captured by imaging the scene directly onto a two-dimensional sensor array comprising of $N \times M$ detector elements. On the other hand, an identical two-dimensional representation of the same scene can also be captured by scanning a one-dimensional sensor array comprising of $N \times 1$ detector elements along the orthogonal axis. The motion of a vehicle/platform is typically used to perform the orthogonal 'sweep' in this 'push-broom' approach.

2.3.5 Cost/performance of hyperspectral imaging systems

While the existing hyperspectral imaging systems are much too expensive for vehicular ASDASs and applications, it may be possible to reduce the number of sensor detectors as well as the number of spectral bands of a hyperspectral imaging system to significantly reduce hardware costs and operational complexity without sacrificing functional reliability.

Technological advances in the field of multi-colour detectors that can select spectral bands through tailoring of the band gap in the device design may also enable substantial cost reductions, just as in the case of current video camera CCD arrays. Note that these devices have exact pixel registration for each of the wavelengths and can be made in two-dimensional detector arrays using standard microelectronics manufacturing techniques.

2.3.6 Hyperspectral imaging technology change in the near-, mid- and long-term

In the near-to-mid-term, the hyperspectral imaging technology will be driven largely by the defence community (government as well as industry) for intelligence, surveillance and reconnaissance types of applications. There has been considerable interest in combining visible, short-, mid-wave- and long-wave-infrared imagery in real-time to produce an enhanced image displayed on a monitor to provide enhanced situational awareness to operators of air-borne vehicles and platforms. Advances in computer vision techniques that have enabled reliable detections of vehicles, pedestrians, animals and street signs will provide a natural extension of current night-vision systems in vehicles and otherwise.

In the long term, improvements in the detector and signal processing technologies will lower the cost of hyperspectral imaging systems and reduce the computational complexity of real-time target material detection and recognition algorithms. Beyond the sensing of many different wavelengths for imaging, additional hyperspectral mapping modalities would likely be realised, which would encompass eye-safe range-Doppler information as well as acoustic and ultrasonic spectral information. In these situations, a multi-dimensional electronic image would be enhanced to include accident avoidance information along with driver advice using optical (range-Doppler) and acoustic returns from various proximal objects. Other novel sensors in development would likely be employed as input transducers for hyperspectral processing, including laser-based remote sensors, fibre sensors, compensated vibrometers, etc.

3 Over the horizon (OTH) imaging sensor technologies and technology gaps

We have conducted literature searches and patent surveys to evaluate a number of imaging sensor technologies that would impact future vehicle ASDASs. We reviewed the state-of-the-art and the technology trends in different time frames to identify OTH technologies and technology gaps for each sensor that promise improved cost/performance for future ASDAS applications. Discussions on these OTH sensor technologies and technology gaps for specific sensor modalities are presented in the following subsections. Table 1 summarises the key technical thrust and the technology gap of each OTH sensor technology. The table also rates the impact on ASDAS architecture, data fusion and vehicle integration for each OTH sensor technology along with the technical gap and projected development cost.

3.1 Vision sensors

While smart CMOS vision sensor research continues, no high-resolution smart vision sensor has yet been demonstrated that offers a variety of programmable processing options, has performance superior to more conventional digital processing of sensor images and is practical for automotive applications, especially from the cost and packaging perspectives. This is due in large part to the fact that when imaging and data processing functions are combined in the same physical pixel structure, active pixel designs that jointly optimise both functions pose a technical challenge. Other technology gaps include:

- Multiple Field-Of-View (FOV) vision sensor systems for forward collision warning. The majority of the vision sensors are single field-of-view sensors which cannot meet the conflicting imaging requirements of being able to image multiple lanes in close (wide FOV) and imaging lane markers at long distances (narrow FOV). With the cost of imaging sensors, image processors and fixed (plastic) optics decreasing, a vision subsystem that incorporates multiple imaging sensors with different FOVs is feasible and should improve performance in terms of long range lane recognition and object detection.
- Incorporation of active illumination for inclement weather or bad visibility situations. Most of the vision sensors are passive systems that rely on natural illumination for image capture, with active illumination only used for night time driving. The use of

Table 1 OTH imaging sensor technologies for vehicle active safety and driver assistant system applications

OTH sensor technology	*High resolution and high dynamic range CVS*	*Smart CVS*	*3D CVS*	*Networked CVS*	*Computer vision algorithms*	*Mid-to-Far range IR detectors and imagers*	*Low-cost multi-spectral sensors*
Key technical thrust	Increase CVS dynamic range and pixel counts	Active pixel with on-pixel processing	Pulse LED active illumination + time gated circuits	Multiple FOVs for full vehicle scene	Enhanced visibility and display	Mid-to-Far IR optical detectors (and sources)	Sensor spectral selection and coordination
Technology gap	Cost (for meeting VASS performance requirements)	Cost + Tech (for active pixels sensor development)	Cost + Tech (for active illuminator and range processing)	Cost + Tech + Integration (multi-sensor data fusion)	Tech (for VASS task-specific algorithms)	Cost (for QWIPS detector and QCL laser)	Cost + Tech (for low-cost multi-band sensor and processing)
Impact on VASS architecture	Low	Low	Low	Moderate	Moderate	Low	Low
Impact on vehicle integration	Low	Low	Moderate (active illuminator)	High (multiple CVS sensors)	Low	Low	Low
Impact on sensor fusion	Low	Moderate	Moderate (object range)	Moderate (sensor + FOV coordination)	High	Low	High
Impact on VASS applications	Improve vehicle scene resolution	Offer coarse feature and motion extraction	Offer scene image with coarse range information	Offer 360-deg vehicle scene	Improve vehicle scene understanding	Improve sensor performance in bad weather	Improve vehicle scene understanding
Projected technology development cost	Low	Moderate -high	Moderate -high	Moderate - low	Moderate -high	Moderate - high	High

near-IR (or even visible) active illumination for improving image capture in inclement weather or in challenging environments (tunnels, shadows) should be investigated. The illumination can also be coded spatially and temporally to enable superresolution using computational imaging techniques (Rangarajan et al., 2009).

3.2 IR imaging sensors

A technology gap in IR sensors and IR image processing is in the area of 3D IR imaging. 3D IR imaging is currently not being investigated because of the high cost of IR sensors. However, assuming that IR technology will evolve to make low cost IR sensors feasible in the next 5–10 years' time frame, 3D IR imaging offers the potential of providing all-weather, high-resolution range and intensity information for advanced driver assistance and ASDAS applications. 3D IR imaging could be achieved through the use of pairs (stereo) of IR imaging sensors (more near term) or using techniques similar to the 3D vision sensors described in Section 2.1.2. Along with the development of 3D IR imaging sensors, there is a need to develop image processing algorithms that exploit the range and intensity information provided by these novel sensors.

3.3 Hyperspectral imaging sensors

Multi-spectral and hyperspectral sensors offer the potential to identify objects through their material properties. Current fielded systems, which are used in remote sensing applications, are expensive because of the detector array size and the number of wavelengths collected and processed. However, if the total number of detected wavelengths is reduced, the cost of the sensor and the processing complexity can be greatly reduced. Therefore, one technology gap for multi-spectral sensors is the determination of the specific wavelengths or finite number of wavelength bands that optimally support the sensing (object detection/recognition, lane recognition, etc.) needs of a vehicle for ASDAS. With judicially selected spectral bands and matching exploitation and fusion algorithms, a compact, potentially low cost, multi-spectral sensor could be developed for ASDASs, providing the novel capability of detecting and classifying objects on the basis of both shape and spectral features.

4 Conclusions

In this paper, we discussed imaging sensor technologies for vehicle ASDAS applications. We summarised the technical characteristics and evolutionary status of ASDAS imaging sensors along with our evaluation of over the (technical) horizon (OTH) sensor technologies that promise new and enhanced capabilities for future ASDAS applications. The criteria we have used in our evaluations for each OTH technology are technological feasibility, potential performance/benefits to vehicle ASDASs and overall system cost and deployment of the technology.

Table 2 presents a projected timetable, over different time frames, for the development of these OTH sensor technologies for ASDAS applications. We also present detailed discussion on the technical status of each sensor and associated OTH technologies in the following.

Table 2 OTH imaging sensor technology development

OTH sensor technology	*Near-term*	*Mid-term*	*Long-term*
High resolution and dynamic range CVS	X		
Smart CVS			X
3D CVS		X	
Networked CVSs	X		
Computer vision algorithms	X		
Mid-to-far IR detectors and imagers	X		
3D IR imagers			X
Low cost multi-spectral sensors			X

4.1 Vision sensors

Of all of the sensor systems evaluated, vision sensors will be the lowest cost and highest performance sensors because they benefit from the high volume of the digital camera consumer market and the increasing processing capabilities from Moore's law and from algorithm developments in the military and homeland security markets and applications. The main limitation of vision sensors is degraded performance in poor visibility conditions (inclement weather, smoke, etc.). The main technical challenges for vision sensors are the development of low cost high dynamic range sensors and the development of robust image-processing algorithms.

Existing imaging sensors currently have performance (resolution, dynamic range) that is for the most part adequate for many vehicle ASDAS functions (backup warning, lane change assistant, lane departure warning, pedestrian detection, etc.). The low cost of imaging sensors permits cost-effective multiple sensors in networked configurations for 360 degree sensing, stereo sensing and multiple field-of-view configurations for meeting the requirements of a variety of challenging vehicle ASDAS applications (e.g., long range forward collision warning).

Directions for development in the sensor area include development of high dynamic range imaging sensors, investigation of multi-camera networked CVS configurations (360 degree imaging, multiple field-of-view systems) and investigation of the use of active illumination to improve image capture. Similarly, directions for development in the algorithm area include development of lane recognition, object detection, tracking and classification algorithms, algorithms that exploit colour and stereo imagery (since colour and stereo sensors will also be low cost) and imagery from multi-camera systems.

Longer term investment should be directed toward 3D imaging chips and exploitation of 3D information. Although 3D time-of-flight imaging chips (used, e.g., in flash lidars) are a much newer technology than either radar or LADAR, it has the greatest potential to be a low cost, reliable 3D sensor, because the sensors are fabricated using CMOS technology and require no moving parts or expensive detectors. Initial versions of near-IR time-of-flight 3D imaging sensors have been developed. Although the range resolution is relatively coarse and the maximum range needs to be improved for ASDAS applications under sunlight conditions, it is expected that in the near- to mid-term time frame the performance and cost will improve sufficiently for automotive applications.

4.2 IR imaging sensors

Mid-to-far IR imaging sensors with extension into millimetre wave (mmW) range provide similar sensing capabilities as vision and near IR imaging sensors with improved performance at nighttime and in poor visibility conditions (inclement weather, smoke), because they can be tuned to operate in an atmospheric transmission window to reduce signal loss.

Mid-to-far IR and mmW imaging sensors do not have a high volume market or application (like the digital camera market for visible light imaging sensors) that would drive down cost and push improvement in performance (higher resolution, higher dynamic range); therefore, we recommend development of mid-to-far IR and mmW detector technology and imager prototype for ASDAS applications. Image processing algorithms for mid-to-far IR imagery are similar to those used to process visible imagery. The use of IR imagery for object detection, tracking and recognition has been demonstrated (and deployed) primarily in military applications. In the near term, algorithms for lane recognition, road curvature estimation and object detection/tracking/classification for vehicle ASDAS applications will be developed. Because of the rapid advances being made in the areas of semiconductor lasers (for active illumination) and in IR detector technology, we expect that mid-to-far IR imaging sensors will become cost effective for vehicle ASDAS systems in 5–10 years.

In the mid-term, the focus should be on cost reduction of IR sensors, on the development of lane recognition and object detection, tracking and classification algorithms and on techniques to fuse IR imaging sensor with either visible, RF radar or LADAR sensors. Longer term investment should push the technology towards 3D IR imaging, which could be achieved through the use of pairs of IR imaging sensors (stereo) or through the development of 3D IR imaging chips similar to the 3D vision sensors described in Section 2.1.2. Long term investment should also include the development of algorithms to exploit the range and intensity information provided by the 3D IR Imaging sensors.

4.3 Hyperspectral sensors

Multi-spectral and hyperspectral sensors offer the potential to identify objects through their spatial and material properties. Hyperspectral processing can take advantage of the different spectral signatures of materials to identify objects that are partially obscured or at a farther distance than systems that rely on a single spectral band detector. However, this technology is currently not practical or cost effective for automotive applications in a 7–10 year time frame.

Technology breakthroughs that would make multi-spectral/hyperspectral sensors more attractive include: determination of the specific wavelengths or finite number of wavelength bands that optimally support the sensing (object detection/recognition, lane recognition, etc,) needs of vehicle ASDASs, the integration (common aperture, integrated set of detectors and read-out hardware) of these selected spectral bands into a low-cost sensor and the development of exploitation and fusion algorithms to exploit multi-sensor imagery. These developments could result in a low-cost, multi-spectral sensor that would provide novel sensing capabilities for future vehicle ASDAS applications.

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See www.cypress.com/go/imagesensors

Notes

[1]The term ‘smart vision sensor’ is sometimes used to refer to active pixel sensors that extend dynamic range or improve uniformity using pixel-based circuitry. We reserve the term for vision sensors that utilise in-pixel circuitry specifically for extracting information from the imaged scene, as opposed to improving the quality of the detected image.

[2]It is beyond the scope of this report to describe them in detail beyond brief descriptions of functionality and potential applications. More technical details can be found in conference proceedings such as the IEEE Intelligent Vehicles Symposium.